

MANAGING THE SAFETY OF ICE COVERS USED FOR TRANSPORTATION IN AN ENVIRONMENT OF CLIMATE WARMING

Don Hayley,
EBA Engineering Consultants Ltd., Kelowna, BC, dhayley@eba.ca
 Sam Proskin,
EBA Engineering Consultants Ltd., Edmonton, AB, sproskin@eba.ca

RÉSUMÉ

Cet article propose une revue des risques inhérents à la gestion sécuritaire des routes de transport sur couvert de glace. La plus longue et la plus sollicitée des routes de glace du Canada dessert l'industrie minière de diamant dans la partie centrale des Territoires du Nord-Ouest et s'étend jusqu'à la région de Kitikmeot au Nunavut. La tendance climatique au réchauffement que vit le Canada a pour effet de raccourcir la saison d'opération de ce type de route à un moment où la demande du trafic est proche de la limite opérationnelle et tend encore à s'accroître. L'article décrit les améliorations apportées à l'efficacité des routes de glace par le développement de technologies pour améliorer la capacité structurale et par une gestion rigoureuse des risques. Ces améliorations permettent de gérer efficacement une plus grande incertitude sur les conditions d'exploitation tout en maintenant la priorité sur la sécurité des usagers.

ABSTRACT

This paper reviews some of the unique geohazards inherent in developing safe operating procedures for infrastructure reliant on ice covers. Canada's longest and most heavily used ice road services the diamond mining industry in central Northwest Territories extending into the Kitikmeot region of Nunavut. A climatic trend to a diminished operating season is evident at a time when traffic demand is near the operational limit and future traffic growth is predicted. The paper describes improvements in ice road efficiency, load capacity and risk management that have been adopted to cope with greater uncertainties while continuing to put operator safety as the highest priority.

1. INTRODUCTION

Transportation infrastructure in Canada's northern territories is under increasing pressure from resource exploration and development. The high cost of road construction over permafrost terrain and the great distances involved substantially restrict growth of regional transportation systems. Resource projects have therefore relied heavily on winter roads that maximize the use of ice covers. The best known industrial winter road in Canada is the Tibbitt to Contwoyto Winter Road (TCWR). This seasonal transportation system begins 70 km east of Yellowknife at the end of Northwest Territories Highway No. 3 and extends 600 km northeast into the Kitikmeot region of Nunavut. It has been the sole re-supply route for Canada's new diamond mining industry for more than a decade. The routing follows old trappers' trails, portaging from lake to lake such that 85 percent of the route lies over lake ice. The high seasonal traffic frequency, up to 11,000 loaded trips north in 72 days (2007 season), coupled with 64 tonnes normal Gross Vehicle Weights (GVW), has provided challenges to managing the risk of breakthrough. The objective of this paper is to describe the evolution of ice road risk management procedures for industrial ice roads. Those procedures have evolved from technology developed in Canada over the past 40 years for public winter roads.

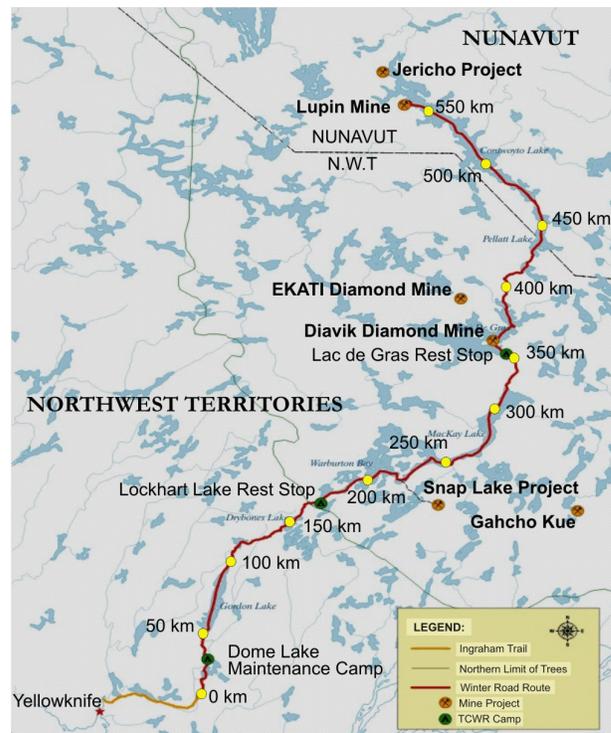


Figure 1. Tibbitt to Contwoyto Winter Road

2. EVOLUTION OF OPERATING GUIDELINES

Provincial and Territorial transportation authorities that have a program to remote northern communities have established guidelines for assessing the safe carrying capacity of an ice sheet. The procedure for determining a safe operating capacity for vehicles of specific GVW is proportional to the square of the thickness of the ice sheet. The simplified Equation [1], presented by Gold (1971) in his classic paper "Use of Ice Covers For Transportation", is used throughout Canada.

$$P = Ah^2 \quad [1]$$

where:

- P: is the allowable GVW (kg)
- A: is a lumped parameter that reflects the critical stress in the ice sheet and load distribution (kg/cm^2), and
- h: is the thickness of the ice sheet (cm).

Gold was able to calibrate Equation [1] using data he accumulated over a number of years on ice sheet failures and successes. That data is re-plotted from Gold's original paper in metric units in Figure 2. Gold identified three critical bounds that represent a realistic range of risk associated with any chosen A-value. The three bounds suggested by Gold, also shown in Figure 2, are:

- A of 3.5 is an operating condition considered safe where failure is unlikely,
- A of 7 is the suggested upper limit for normal operations on ice, and
- A of 17 is the limit above which failure should be anticipated.

Ice road operational data reported in Figure 2 shows considerable overlap between ice road failure and success. There are an appreciable number of failures at stress levels for equivalent A-values above 3.5 that would not be predicted using theoretical bearing capacity analyses. These can generally be explained by considering other factors such as cracks produced by thermal contraction, stress amplification caused by hydrodynamic effects, or unforeseen stationary loads such as snow banks. The challenge of an ice road safety management plan therefore becomes striking an appropriate balance between the stress parameter A and the degree of vigilance and control the agency is prepared to impose on the opening and operation of the road. This will depend on the road usage and the importance of maximizing the safe working load. An operation designed for moving drilling equipment around the Mackenzie Delta or re-supplying fuel to diamond mines will need different operating parameters than a road that provides a service for residents of isolated communities to connect with their pickup trucks and grocery trucks during the winter months.

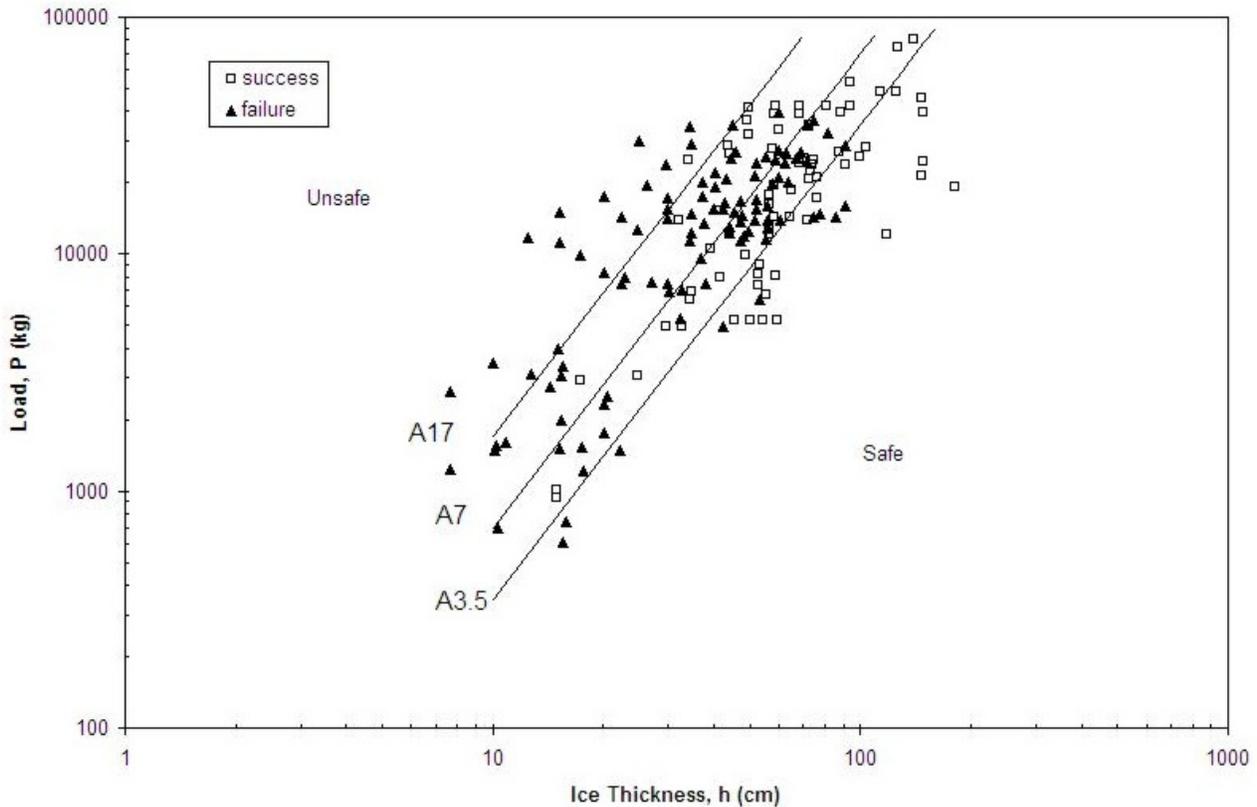


Figure 2. Load vs. Ice Thickness Data for Successful Use and Failures of Ice Covers (Gold 1971)

Figure 3 puts the limits suggested by Gold into a commonly used risk paradigm. The agencies that adopt the Gold equation for their guidelines must balance the level of risk with operational controls if they are to operate with a guideline A-value much above 3.5. Figure 3 also shows the values that are used by certain Provincial and Territorial Governments. Those jurisdictions that accept an A-value of 7 also discount by ½ the component of the ice sheet that is not natural "blue" ice as white ice caused by over-flooding or slush. The TCWR, which is mostly within the Northwest Territories, had adopted an ice capacity criterion equivalent to about A(6) and does not discount the ice sheet thickness when flood ice is encountered. This experience-based guide, which is above the regional criteria of 4, was used up to the year 2000, when traffic frequency and load magnitudes were on a steep increasing trend. About that time, overall safety of the operation came under scrutiny following breakthrough of two snow cats during early season snow clearing. The challenge was to legitimize the many years of experience with technology that would optimize operating parameters while maintaining operator safety as the highest priority.

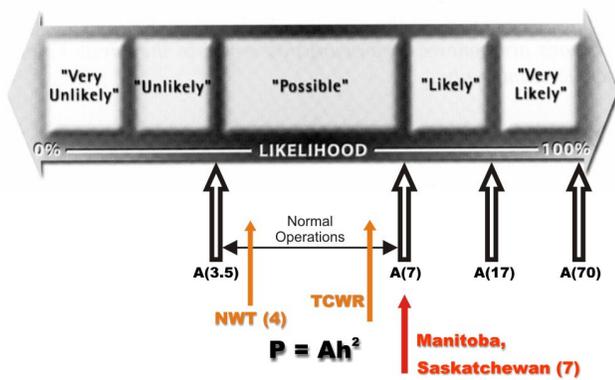


Figure 3. Characterizing Failure Risk

3. CALIBRATION FOR VEHICLE TYPE

The Northwest Territories Department of Transportation had established their guideline for public ice roads based on a relatively conservative A-value of 4. This safety threshold is considered appropriate for the level of control applied during their road operations. By 2000, it was apparent to the operators of the TCWR that adoption of the Northwest Territorial guideline was not an option as the limitations on road capacity would be too severe for it to fulfill its intended function. The contractor had gained twenty years of valuable experience that provided a rational basis for operating at higher load levels. Effective procedures had been implemented by then to limited vehicle type, spacing and most importantly speed. These limitations were coupled with a vigilant ice thickness quality control program using radar and speed enforcement by a private security force.

The experience-based measures implemented by 2000 were clearly effective, but they had little theoretical support for deviating from what could be considered the regional

standard of practice. It became important to review work done in the 1960s and modernize it for the types of vehicles that are now using industrial winter roads in order to use a higher proportion of the risk-based range identified by Gold for determining ice capacity. The data presented by Gold was limited to ice less than 1 m thick and was based on a certain class of trucks in common use in the 1960s, similar to tandem gravel trucks (Gold 2001). The maximum size of vehicle used to haul fuel on the TCWR in 2000 was a B-train with double trailers and seven axles, operating at a fully loaded GVW of 56,000 kg.

The procedure described by Hayley and Valeriotte (1994) for determining ice capacity for long vehicle types and relating it to the Northwest Territories guideline (A = 4) was used to compare and calibrate maximum tensile stress on the ice sheet for the two loading configurations: gravel truck and B-train. The deflection and stress in the ice sheet were calculated using a closed form solution developed by Wyman (1950). A program was written to relate the maximum tensile stress at the bottom of the ice sheet to a series of circular loads representative of dual or single wheel configuration at typical tire pressures. Back analyses of the gravel truck indicated that there was a reasonable match between Gold's equation with an A-value of 4 and the stress analyses for stresses that vary from 600 kPa to 700 kPa for ice thicknesses in the range 25 cm to 100 cm. This stress range was therefore adopted as a reasonable working stress for the ice that did not compromise safety relative to the guidelines developed and applied within the Northwest Territories. It was compared with other literature such as Masterson and Gamble (1986), who did a similar analysis using the Westergaard formulation (Westergaard, 1947) and recommended a working stress of 550 kPa. The advantage of the Wyman's solution was that a better representation of load distribution for long vehicles with multiple axles was possible.

4. WORKING STRESS AS AN ICE SERVICEABILITY CRITERION

Field studies on floating ice covers have shown that, under increasing load, a sequence of cracking leads to breakthrough failure. First, radial tensile cracks develop on the bottom. Second, circumferential cracks develop on the upper surface at some distance from the load as loading is increased toward a failure condition. Eventually, breakthrough usually occurs when vertical circumferential shear planes develop close to the load. The breakthrough load has been observed to be 2 to 4 times greater than the load that causes initial cracking (Peters *et al.* 1982 and Sodhi 1995).

Peters *et al.* (1982) and Masterson and Gamble (1986) proposed that the ice cover bearing capacity be based on serviceability criterion associated with initial radial tensile cracking of the ice cover. This criterion has the following advantages:

1. It has an inherent built-in factor of safety of 2 to 4 since breakthrough occurs at higher loads.

2. The model of floating ice as an elastic plate resting on a Winkler elastic foundation can be used to calculate the flexural tensile stresses that lead to initial tensile cracking.
3. An observational approach can be used to detect radial cracks and circumferential cracks as warning signs of exceeding the serviceability criterion.

The serviceability criterion is defined as the load at which the flexural tensile stresses at the bottom of the plate (ice cover) reaches an allowable stress that maintains the ice sheet in an elastic condition and does not produce radial cracking. This working stress design approach requires estimation of the allowable flexural tensile stress for the field and ice conditions under consideration. The strength of ice varies with its temperature, strain rate, structure (crystal orientation or type of ice). Given the difficulties in obtaining reliable laboratory and field ice strength measurements (Kivisild 1975, Ashton 1986 and Gold 1987), a back-calculated value of allowable flexural tensile strength of 550 kPa has been widely used (Masterson and Gamble 1986). A review of past literature conducted by Gold for this project recommended 600 kPa as a practical criterion (Gold 2001). The values used by EBA Engineering Consultants Ltd. range from 500 kPa for early season, thin ice conditions during road opening to 700 kPa for late season ice in excess of 1.2 m thick.

Selection of the appropriate allowable stress not only depends on the route characteristics and ice conditions but also the degree of confidence in quality and uniformity of the ice cover. Quality and uniformity of the ice cover will depend on the contractor following good practices in clearing snow and, if necessary, flooding to build ice. Standard operating procedures that mitigate risk must be developed and enforced by the road operating authority to achieve those objectives.

5. OPERATING PROCEDURES THAT MITIGATE RISK

Operating experience on the TCWR, during the past seven years (2000 to 2007) following formalization of an ice risk management program has shown that the over-ice component can function safely using an ice capacity criterion based on maximum stress analyses. The criterion applied to eight-axle Super B-train trucks with highway legal load (GVW) of 63,500 kg is approximately equivalent to use of the Gold equation with an A-value between 6 and 7. There is no distinction made between natural "blue ice" and white flood ice for determining total ice thickness.

There has been only one potentially fatal breakthrough during road operations once it has been opened for truck traffic. A total of 58,000 loaded trucks used the road during that seven year period. Figure 4 shows the operating failure that occurred in 2001, with the fuel tanker trailers floating following breakthrough and the tractor remaining on the ice surface. It was fortunate for the driver that the density of diesel fuel provided sufficient buoyancy for the trailers to remain afloat, thus the tractor stayed on the ice. The outcome could have been much different if the truck had

been carrying cement, blasting supplies or other heavy commodities needed for mining operations. Approximately sixty percent of the heavy vehicles using the road are fuel tankers of the type shown in Figure 4.



Figure 4. Failure due to speed-related blowout, March 2001

The risk that ice breakthrough poses for the driver can be crudely compared with that from rockfalls on certain highways in British Columbia using the procedure described by Bunce *et al.* (1997). The probability of a fatality following a breakthrough of this type is assumed to be in the order of 1 in 10, similar to that of a rock striking a vehicle and causing a fatal accident. The data is insufficient at present to provide a definitive risk assessment; nevertheless, it appears that driving on a well managed ice road does not expose drivers to greater risk than many BC highways.

This particular incident occurred at a time and location when the ice thickness met the criterion for the serviceability load. The breakthrough was attributed to fracturing of the ice by a loaded truck that was exceeding the set speed of 25 km/h. The driver of the vehicle shown in Figure 4 was unaware that the truck ahead had created a perilous situation by disregard for established operating procedures.

The failure incident highlights the importance of mitigating risk of breakthrough by establishing and enforcing operating procedures that focus on those factors that are not explicitly included in the computation of ice serviceability limit stress. Moreover, it is equally important that all equipment operators on the road understand the need for these procedures and how they fit into the overall safety management plan and standard operating procedures. The objective is to operate the road at a risk level consistent with trucking operations over land in regions with genuine terrain-related risks such as landslides, rockfalls and washouts.

Failure risk is always greater during the period of road opening. The ice is thinner and initial snow cover masks cracks that form early in the season from thermal contraction. Most of the fatalities that have occurred on ice roads in Western and Northern Canada occur during that critical period of road opening. They can usually be related to inexperienced operators, lack of knowledge of basic equipment characteristics and inappropriate contingency

safety planning. Greater conservatism needs to be used during this period and an emphasis placed on operator awareness and contingency planning for a potential breakthrough.

The principal features of a risk mitigation plan for industrial, high capacity, over-ice roads include the following.

5.1 Speed Control

Studies have shown that a moving truck produces waves in the ice that are transmitted to waves in the water below the ice cover. The deflected shape of the ice remains consistent up to a vehicle speed that is 70 percent of the “critical speed” (Eyre and Hesterman 1976). As the vehicle approaches the critical speed, a secondary wave develops in the ice ahead of and behind the vehicle. These induced waves amplify the deflection and, therefore, the stress in the primary wave. The amplification effect has been shown to depend on water depth and ice thickness. A rapidly diminishing water depth, such as shore approaches, requires vehicle deceleration coupled with direction change to avoid pressure build-up under the ice.

The overall routing of the TCWR is through rugged Canadian Shield country where exposed rock is the common shoreline, as shown in Figure 5. The lake bottoms are equally as rugged as the surrounding terrain; therefore, water depth is constantly changing as the routes pass over rocky shoals beneath the ice. Early studies showed that, even with a low speed limit of 25 km/h reducing to 10 km/h at shore crossings, the trucks were at risk of operating near the critical speed for water depths less than 5 m. The waves created in shallow water near shoals can fracture the ice at the contact where the ice is frozen to the bottom, resulting in a condition known as “blowouts”. These blowouts, such as the one shown in Figure 6, can remain active all season, pumping free water to the surface with each passing vehicle.



Figure 5. Typical terrain along the TCWR



Figure 6. Speed-related ice blowout, TCWR

5.2 Over-ice Route Selection

The presence of blowouts along the shorelines of smaller lakes and well away from the shorelines in lakes with rugged shore topography highlighted the need to carefully select a route over lake ice. It was not sufficient to adopt the route across the ice with the shortest length. Over a period of years, data was collected on ice behaviour and bathymetry and the routes were continually refined to take advantage of deep water. Mapping and relocation of the over-ice route each year was simplified using state-of-practice GPS technology.

5.3 Continuous Ice Thickness Profiling

Ice thickness determination is a two-stage process, with the contractor using Ground Penetrating Radar (GPR) for daily assessment at the quality control stage. This has been followed by independent verification using a GPR system that is customized to determine ice thickness, ice grounding and water depth below the ice on a single pass. This system is operated by geophysicists and fully spatially rectified using differential GPS. The results allow archiving of data sets and rapid recall of information for quality assessment purposes. The dual channel radar system is shown in Figure 7.

5.4 Crack Surveillance and Surface Maintenance

The road surface must be inspected frequently to identify wet cracks, effects of snow bank build-up and surface deterioration. These features are repaired by flooding. Figure 8 shows an ice road surface in need of repair by localized flooding.

5.5 Traffic Control and Operator Orientation

Traffic control is required for both operating safety and ice surface management. Traffic controls are of limited use without enforcement. The road must be continuously monitored by security forces using radar speed detectors. These operating procedures are reinforced with a driver

orientation process that educates all drivers on the purpose of operating limitations such as speed limits, vehicle spacing and stopping on ice. The process has proven very effective at improving operator cooperation and building a sense of caring for the welfare of other drivers.



Figure 7. Dual channel ice radar system for combined ice thickness and water depth.



Figure 8. Common longitudinal cracking from wear and tear on the ice road surface

6. CLIMATIC RISKS

The necessity to optimize operation of the TCWR has been driven by a combination of increasing traffic volumes coupled with greater climatic uncertainties. Winters are less severe than when the road was first opened, but more importantly, there are greater deviations from past normal conditions. The parameter that seems to best relate climatic variability with ice growth and stability is the air freezing index. A combination of winter month air freezing index and snow cover controls the rate of natural ice growth and the ability of the ice sheet to sustain loads late in the season. The freezing index variability for the southern route segment is represented by the historic data from Yellowknife shown in Figure 9. The freezing index is predicted to diminish at a rate of 174 C° days per decade or a loss of about 0.5% of the available freezing capacity every decade. The freezing

index has been crudely correlated with the historic operating season in Figure 10, which suggests that a normal season is currently about 65 days; this could drop to only 54 days by the time the traffic reaches its projected peak in 2020. These predictions have stimulated a thorough review of adaptation strategies that are most appropriate for the near term, the medium term and the longer term.

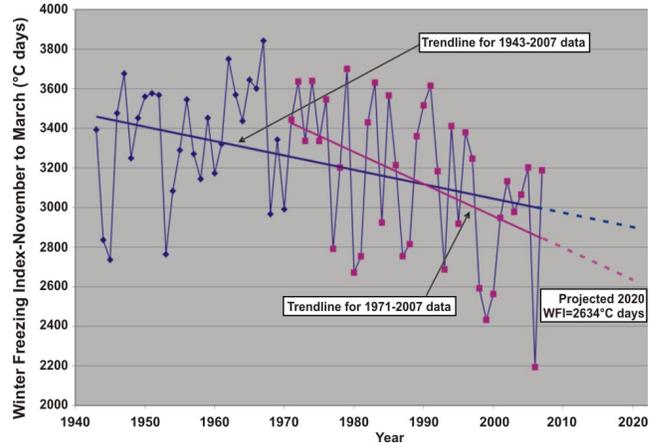


Figure 9. Summary of Yearly Freezing Index for Yellowknife

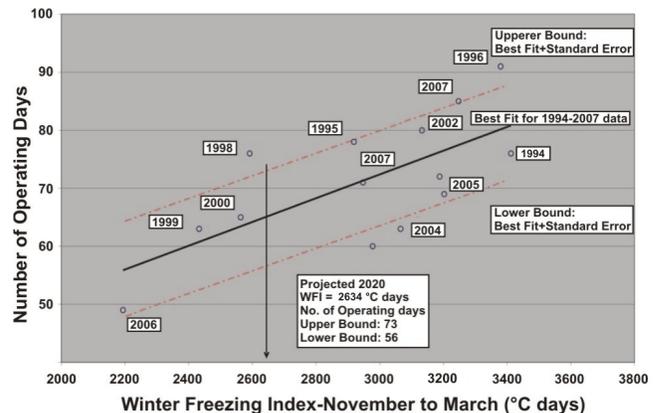


Figure 10. Correlation of Yearly Freezing Index for Yellowknife with Operating Season

Medium or long term strategies that involve moving off the ice would have a time frame associated with design, environmental studies and permitting before construction could begin. These activities normally require a five-year planning and implementation window. The focus remains on optimization of traffic over the ice road without compromising safety. This strategy has resulted in implementation of several key measures, including:

1. Traffic management by express lanes to separate loaded trucks from returning trucks allowing the speed restrictions on the returning trucks to be relaxed,
2. Implementation of multiple routes across lakes with known ice instability to allow rapid traffic redirection in the event of local ice deterioration, and
3. Development of parallel winter road routes where practical.

7. CONCLUSIONS

Winter roads that use ice covers for transportation are now common infrastructure for northern resource development. The risk of breakthrough when heavily loaded trucks are operating over ice is a hazard that must be managed by application of state-of-practice technology. An operation of the magnitude of the TCWR has provided an opportunity to enhance and adapt technology developed in the 1960s for public winter roads. This has led to clearer understanding of the risks and how they can be effectively mitigated by operating procedures. These processes are essential in order to make the operations feasible. The feasibility continues to be challenged by unfavourable climatic warming trends.

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